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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

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WAKE SCALE EFFECTS AND PROPELLER HULL INTERACTION:

STATE OF THE ART

by

CARL SCRAGG

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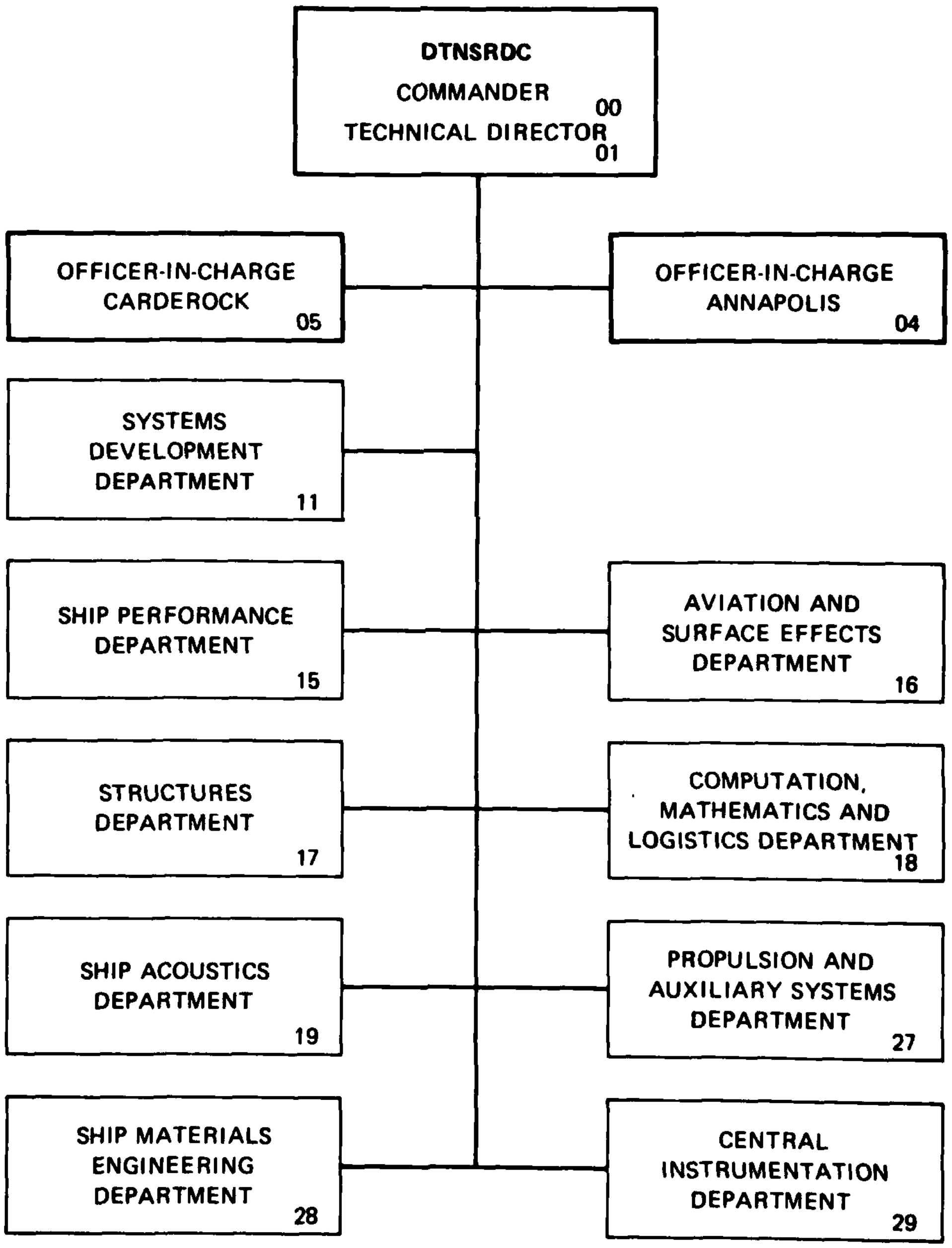

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This survey reviews the progress of research on the dual problems of wake scale effects and hull propeller interactions. The survey covers theoretical, empirical and experimental results. The state of the art is defined in terms of those hull forms which have wakes which can be adequately predicted using currently available techniques. Suggestions of the manner in which the state of the art might be extended are presented.

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NOTATION

a	Axial distance measure from airship nose in Fig. 3
C_{Th}	Thrust loading coefficient, $= \dfrac{T}{\frac{1}{2}\rho V_A^2 \frac{\pi D^2}{4}}$
C_{TN}	$= \dfrac{T}{\frac{1}{2}\rho V_A^2 (1-w_N)^2 \frac{\pi D^2}{d}}$ (ref. 64 p. XII 32)
D	Diameter of propeller
H	Total pressure head
h	Factor from momentum theory to approximate full-scale propelled wake
J	Advance coefficient, $= V_A/nD$
L	Length of ship
n	Rate of revolution
p	Local static pressure
p_o	Static pressure at infinite upstream; reference pressure
R_T	Total towed resistance
(r,θ,x)	Cylindrical coordinates
r	Radial distance measured from the body axis in Figures 1 and 2
r_o	Radius of the body surface in Figures 1 and 2
r_{max}	Maximum radius of body in Figures 1 and 2
T	Thrust at propeller
t	Thrust deduction fraction, $= \dfrac{T-R_T}{T}$
U_p	Axial velocity profile with propeller in Figures 1 and 2
U_x	Axial velocity profile of the nominal wake in Figures 1 and 2

NOTATION (CONTINUED)

V	Speed of ship
V_A	Speed of advance of propeller
V_d	Velocity obtained from potential theory
V_e	Axial effective velocity
V_N	Axial velocity of the nominal wake
V_M	Model speed in Figure 4
V_o	Value of V_d at the body surface
V_P	Axial velocity in front of the operating propeller
V_S	Free stream velocity in Figures 1 and 2
$\underset{\sim}{V}$	Perturbation velocity in cylindrical coordinate, $= (v,w,u)$
v_x	Velocity component in x-direction in Figure 4
w	Mean wake fraction (p 20)
w_d	Displacement wake fraction
w_e	Effective wake fraction, $= 1-V_e/V$
w_f	Frictional wake fraction
w_N	Nominal wake fraction, $= 1-V_N/V$
$\bar{w}$	Mean nominal wake fraction
w_P	Propelled wake fraction, $= 1-V_P/V$
w_Q	Taylor wake fraction determined from torque identity
w_T	Taylor wake fraction determined from thrust identity
Δw	Change in wake fraction

NOTATION (CONTINUED)

δ	Boundary layer thickness in Figure 3
ρ	Mass density
ψ	Stream function

Notes on subscripts

e	effective
I	induced
m	model
N	nominal
P	propelled
S	ship

ABSTRACT

This survey reviews the progress of research on the dual problems of wake scale effects and hull propeller interactions. The survey covers theoretical, empirical and experimental results. The state of the art is defined in terms of those hull forms which have wakes which can be adequately predicted using currently available techniques. Suggestions of the manner in which the state of the art might be extended are presented.

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INTRODUCTION

Over four decades ago, at the Third International Towing Tank Conference, Troost[1*] stressed the importance of the wake scale effects upon the prediction of full scale powering requirements from test results. Noting that the theoretical development at that time was not advanced enough to permit the calculation of the effects of scale, he concluded, "For the present, one shall have to make use of empirical coefficients to pass from model to ship." In 1975, at the Fourteenth International Towing Tank Conference, Yokoo[2] presented a review of recent research on the determination of the wake field. He reported that it "is very difficult to obtain the wake characteristics theoretically . . . ." Yokoo went on to present a review of state-of-the-art empirical techniques for the determination of full scale wake characteristics.

It is not intended to imply that there has been a lack of interest in the area of wake scale effects, nor is it intended to belittle the efforts which have been put forth during this period. Rather, we wish to illustrate the enormous difficulties of the problem at hand, and the importance which has been, and continues to be, attributed to it. As Yokoo[2] concluded, "a correct answer to the scale effect of the wake is urgently desired, including an improved formula to obtain both wake pattern and vector of the ship."

Indeed, the importance of an accurate prediction of the ship's wake has increased with improved methods of propeller design. It remains an undeniable fact that no propeller design can be any better than the

* references are listed on pages 38-43.

information with which the designer has to work. In a recent paper, Wiegant[3] demonstrated the effects of input parameter errors upon the final design of the propeller, as calculated by the computer program currently in use at Lips B. V. Propeller Works, Drunen, The Netherlands. He calculated the change in the design parameters caused by (1) an assumed ten percent error in measured wake field and (2) the error created by neglecting the scale effects of the wake. The greatest change in the design parameters occurred in the calculation of the camber, which was changed as much as 8% by the measuring error and as much as 20% by neglecting scale effects of the wake.

Clearly, if we wish to obtain the optimum efficiency from the propeller, we must design it properly. But the need for a complete knowledge of the ship's wake is not limited to the calculation of propulsive efficiency. The prediction of full scale thrust, torque, shaft power, and shaft rate of revolution, as well as cavitation and vibration performance, all depend upon the accuracy of our prediction of the full scale wake field. As each of these predictions becomes more important as powering requirements increase, so has the determination of full scale wake increased in importance.

Since there is often some confusion as to the meaning of various wakes, let me digress long enough to supply the following definitions:

(1) nominal wake: $w_N = 1 - V_N/V$, the wake which could be measured at the propeller plane when there is no propeller operating.

(2) propelled wake: $w_P = 1 - V_P/V$, the wake which could be measured immediately in front of the operating propeller.

(3) effective wake: $w_e = 1 - V_e/V$, the propelled wake minus the propeller induced potential flow.

(4) effective wake - thrust identity: w_T, mean effective wake necessary to produce the same thrust in open water.

(5) effective wake - torque identity: w_Q, mean effective wake necessary to produce the same torque in open water.

The last two are not really wake distributions, but are useful concepts. They are calculated by measuring the thrust (or torque) of the propeller operating behind the ship and then using the open water characteristics of the propeller to determine the uniform inflow which would produce the same thrust (torque) at the same rate of revolution. The fact that w_T does not equal w_Q is an indication of the non-uniformity of the inflow. If by some quirk of fate, the inflow to the propeller operating behind the ship were uniform, then $w_T = w_Q = w_e$.

The first three quantities, w_N, w_P, and w_e, are all functions of the position within the propeller disk, and as such are properly referred to as wake distributions. However, only w_N and w_P are measurable quantities. The effective wake must be calculated from theoretical considerations.

The difference between the nominal and the effective wakes is due to the interaction between the propeller and the boundary layer on the hull (indeed, if there were no boundary layer, the two quantities would be identical). The action of the propeller accelerates the flow over the stern. Not only does this result in a decrease in the pressure on the stern, but it also alters the boundary layer, making it thinner and increasing the skin friction. Of course a thinner boundary layer, in general, results in a greater inflow to the propeller. Thus, in general, $w_N > w_e > w_P$. In summary, then, the nominal wake does not include any of the effects of the propeller; the effective wake includes the alteration of the boundary layer caused by the propeller but excludes the propeller induced velocity; and the propelled wake includes both the alteration of the boundary layer and the propeller induced velocity.

The quantity which is of the greatest interest to the propeller designer, the effective wake, is also the most difficult quantity to obtain. It is now a relatively common practice to tow a model and measure the model scale nominal wake with a pitot tube rake. The propelled wake is much more difficult to measure due to the presence of the operating propeller, and the effective wake is impossible to measure. There are several possible approaches one can use in the attempt to calculate the effective wake.

(1) One could measure the nominal wake and "adjust" the measurements (either theoretically or empirically) to account for the alteration of the boundary layer caused by propeller suction.

(2) One could measure the propelled wake and subtract out the propeller induced velocity field. This induced velocity would have to be determined either experimentally or theoretically.

(3) One could attempt to solve the entire problem theoretically.

But, no matter which approach one chooses, the determination of effective wake is a formidable problem, even if one neglects scale effects. Note that only the third approach has an inherent ability to deal with a change in scale. The first two approaches would require an additional calculation if one wished to obtain full scale effective wake from model scale measurements.

Therefore, if we hope to determine the full scale effective wake from model scale measurements, we must attack two separate (but interacting) problems - - the hull propeller interactions and the wake scale effects. The effort which has been directed toward the solution of these two problems has been considerable, yet a general solution continues to elude us. However, the effort has not been fruitless. Theoretical calculations have improved considerably, our understanding of the physical nature of the flow has increased, and a number of empirical techniques have been developed. Let us proceed by examining one of the more successful pieces of research in this area.

A SPECIAL CASE

Recently, a series of papers by Huang et al.[4-7] has dealt with the problem of determining the effective wake distribution of bodies of revolution. Although their present methods are somewhat limited in applicability (axisymmetric bodies, deeply submerged), I will deal with these papers at some length since they represent an exceptional example of the solution of a special case of the problems of wake scale effects and hull propeller interaction.

The nominal wake of an axisymmetric body is calculated by a combination of theoretical and empirical techniques. The potential flow about the body is calculated by the Hess and Smith[8] method and is used as an input to a modified version of the Douglas C S[9] differential boundary layer program. The calculated displacement thickness is then used to modify the geometry of the body. The potential flow program is used again to calculate the pressure distribution on the modified body. The boundary layer program is now used to calculate a new displacement thickness. This iterative process can be continued until two consecutive pressure distributions agree to within a specified accuracy. In practice, it was found that the convergence was of a slow oscillatory nature. For this reason, the authors computed an average pressure distribution from the second and third iteration and then used this average pressure distribution as the input to the final boundary layer calculation.

A comparison of the results of such a calculation with experimental measurements leads to the disappointing conclusion that the method yields good results everywhere except at the stern, i.e., everywhere except the very location in which we are interested. This fact will return to haunt us when we consider three-dimensional bodies.

To obtain the flow at the propeller location Huang must resort to some empiricism. Using integral wake relations given by Granville[10], he calculates the flow in the wake. In the stern region ($0.95 < \frac{x}{L} < 1.05$), it is assumed that neither the boundary layer assumptions nor the far wake assumptions are valid. Within this region, the displacement thickness is modeled by a fifth order polynomial whose coefficients are calculated by requiring that the thickness, slope, and curvature be continuous at $\frac{x}{L} = 0.95$ and 1.05.

Results of wind tunnel measurements of nominal velocity profiles are given by Huang et al.,and are reproduced here (Figures 1 and 2), to show the applicability of the calculations. As can be seen in Figure 1, the agreement between calculated and measured velocity profiles on afterbody 1 (prismatic coefficient equals 0.787) was quite good. The agreement on afterbody 2 (prismatic coefficient equals 0.844), Figure 2, is not quite so good. A third afterbody suffered from flow separation and the results were poor. Their potential flow/boundary layer interaction program is capable of calculating the nominal wake of bodies of revolution of fine to moderate fullness. Such a technique is equally applicable to model and ship scales,provided only that the location of turbulent transition is properly taken into consideration.

The second part of Huang's work provides us with the means necessary for the calculation of the effective wake, using the nominal wake

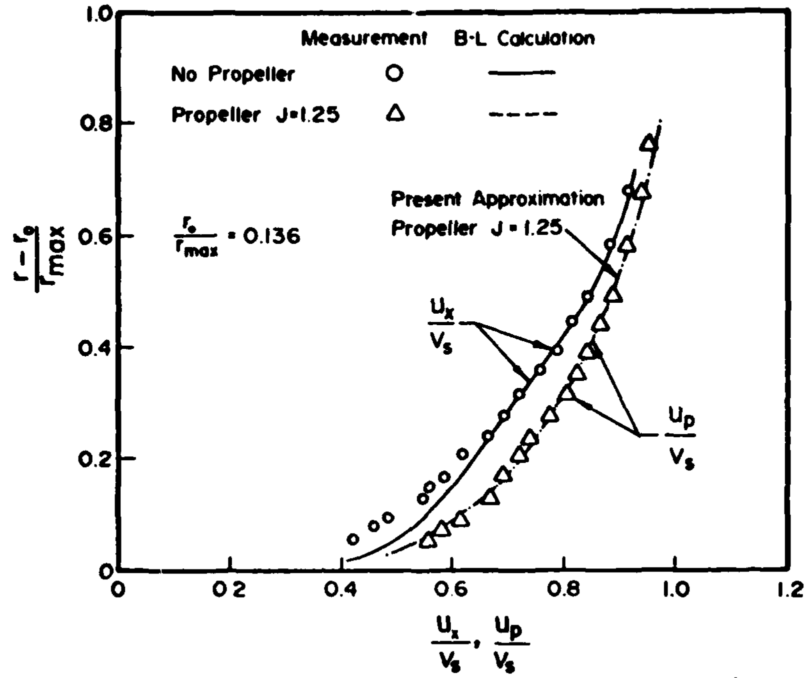

Figure 1 - Huang's results for nominal and propelled wake (afterbody 1). [From reference 6 (Fig. 16e, p. 51)]

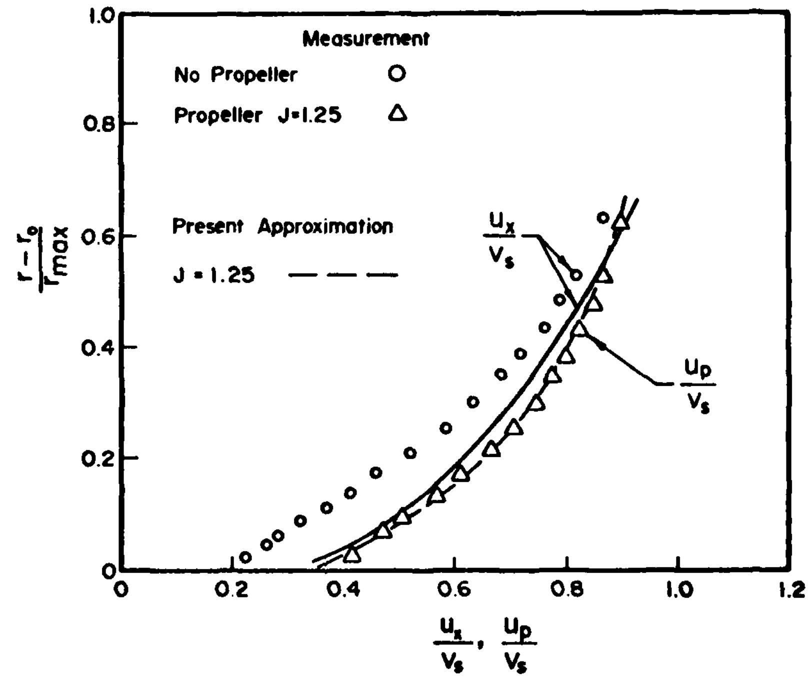

Figure 2 - Huang's results for nominal and propelled wake (afterbody 2). [From reference 6 (Fig. 17e, p. 53)]

(either calculated or measured) as an input parameter. The interaction between the propeller and the thick stern boundary layer is analyzed by inviscid flow techniques. Beginning with the equations of steady motion for an inviscid fluid, written in cylindrical coordinates (r, θ, x), with $\underset{\sim}{V} = (v, w = o, u)$, the authors write the radial component of the equation as

$$u \left(\frac{\partial u}{\partial r} - \frac{\partial v}{\partial x} \right) = \frac{1}{\rho} \frac{\partial H}{\partial \Psi} \frac{\partial \Psi}{\partial r} = \frac{1}{\rho} r u \frac{\partial H}{\partial \Psi}$$

where H is the total head and Ψ is the stream function in axisymmetric flow. It is then assumed that the propeller adds no energy to the upstream fluid and that there is no change in the viscous losses due to the propeller. Therefore, Huang takes the total head within a given stream annulus as being unchanged by the action of the propeller, i.e.

$$\left(\frac{\partial H}{\partial \Psi}\right)_N = \left(\frac{\partial H}{\partial \Psi}\right)_P \quad .$$

It is then assumed that the standard boundary layer assumption holds $\left(\frac{\partial u}{\partial r} >> \frac{\partial v}{\partial x} \right)$, that the induced velocity is irrotational $\left(\frac{\partial v_I}{\partial x} = \frac{\partial u_I}{\partial r} \right)$, and that the radial velocity with the propeller operating may be written as $v_P = v_N + v_I$. We may then write the following relationship between the velocities on the same stream surface in propelled and unpropelled situations,

$$\frac{1}{r_N}\frac{\partial u_N}{\partial r_N} = \frac{1}{r_P}\left(\frac{\partial u_P}{\partial r_P} - \frac{\partial u_I}{\partial r_P}\right),$$

where r_N is the position of the stream surface when no propeller is operating and r_P is the position of the same stream surface when the propeller is operating.

The conservation of mass flow within a given stream annulus provides a second equation and we can, therefore, solve for u_P and r_P if we know u_N and u_I. A simple boundary layer/propeller interaction program has been written for these computations.

Huang then uses the following iterative process to determine the effective velocity distribution:

(1) Given u_N, estimate u_e (for example, let $u_e = 1.1 \times u_N$)

(2) Design a propeller using an existing inverse propeller program, which will provide the required thrust when operating in the estimated effective velocity.

(3) Calculate the induced velocity from the propeller field-point velocity program.

(4) Use the boundary layer/propeller interaction program to compute u_P, given u_N and u_I.

(5) The new effective velocity profile is simply $u_e = u_P - u_I$.

(6) Repeat steps 2-5 until the effective velocity profiles converge. Huang found that three iterations were usually sufficient.

This technique provides us with calculated values of both effective and propelled wakes, using either measured or calculated values of the nominal wake. Figures 1 and 2 compare the calculated propelled velocity distribution with measurements obtained with a laser doppler velocimeter. Notice that the agreement is very good, even on the fuller body for which the nominal wake prediction was less satisfactory.

These results, although directly applicable only to bodies of revolution of fine to moderate fullness, represent the most successful treatment to date of the dual problems of wake scale effects and hull propeller interaction. These papers contain much valuable information and provide an excellent example of the proper approach to the problems. As we shall see, however, the additional complexity inherent in the three-dimensional problem is far from trivial and we may still be some years away from being able to adopt Huang's approach to the problem.

ANALYTICAL BOUNDARY LAYER TECHNIQUES

The first step in the approach, which was outlined in the previous section, is the analytical determination of the turbulent boundary layer on the hull. Once we have obtained a good method for the determination of the boundary layer, we will have conquered the first half of the problem, i.e. the determination of the scale effects on the nominal wake.

In a recent survey of ship boundary layer research, McCarthy[11] reports that, although "significant progress has been made, totally reliable methods are not yet available for computing the thick boundary layers which exist on the afterbodies of either axisymmetric or three-dimensional hulls." One of the primary difficulties can be attributed to the fact that the assumptions, upon which boundary layer theory is based, cease to be valid near the stern. The rapid thickening of the boundary layer was dramatically illustrated by Lindgren[12] when he presented a comparison of the growth of the boundary layer on a flat plate with that on the airship model Akron, Figure 3. With such a flow we may no longer assume that normal derivatives are much larger than longitudinal derivatives, nor may we assume that normal pressure gradients are unimportant. Indeed, one might question whether we ought to be speaking of a boundary layer or simply a viscous flow field.

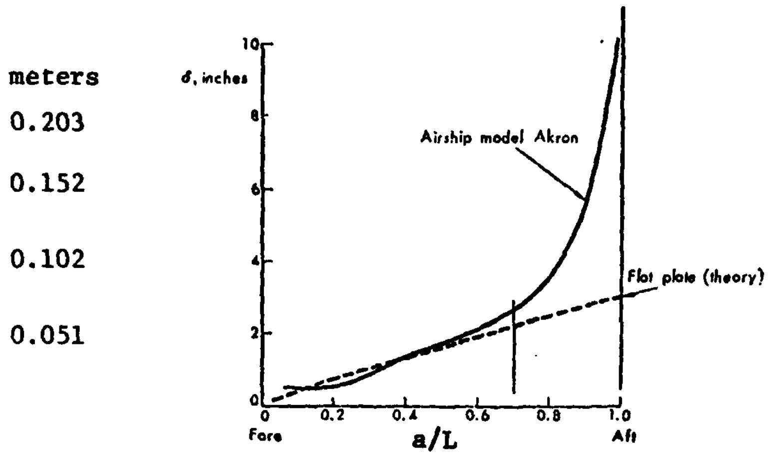

Figure 3 - Boundary layer growth on the model of the airship Akron and on an equivalent flat plate [From NACA Rep. No.430,1932(Fig.4,p.570)]

We have already presented one method of dealing with this problem, Huang's technique of modeling the displacement thickness at the stern of axisymmetric bodies with a fifth order polynomial. Dyne[13] proposed another method recently. In his technique, the flow field forward of the stern is calculated by the use of boundary layer methods, but in the stern region he uses a "streamline curvature" method. In an iterative procedure, he constructs streamlines which satisfy both the continuity and the momentum equations, subject to the assumption that the normal pressure gradient can be simply related to the velocity and the streamline curvature. The technique appears to produce velocity profiles which agree well with the experimental data for the one case for which he presented results.

Another technique for the solution of stern flows on bodies of revolution has been presented by Nakayama, Patel, and Landweber[14]. This is also an iterative procedure and the agreement between calculated and measured pressure distributions appears to be comparable to that obtained by Dyne. However, like Dyne, the authors present results for only one body (with a relatively fine stern) and further investigations are necessary to determine the extent to which their methods will yield acceptable results on a full stern.

These techniques are, of course, directly applicable only for bodies of revolution. When we turn our attention towards three-dimensional bodies, we still face the problem of the thick stern boundary layer, but now we must deal with a number of additional complexities. There will exist a complex interaction between the boundary layer and the potential flow in the presence of a free surface. For the most part, this problem has been avoided by the use of a zero Froude number approximation, but recent papers by Adee[15] and Himeno[16] have suggested new methods of dealing with it.

Even if we ignore the free surface, we must face the probable existence of transverse pressure gradients and accompanying crossflows within the boundary layer and in many cases the crossflows can become separated, producing strong bilge vortices. This phenomenon is especially likely to occur on the stern of full ships but may also occur near the bow. An enormous effort is being exerted toward the solution of three-dimensional turbulent boundary layer problems, and rather than review the recent research here, I will present a few examples of recent attempts to calculate actual ship boundary layers. As well as the review by McCarthy[11], the interested reader should consult reviews of boundary layer research by Granville[17], Larsson[18,19], and Eichelbrenner[20].

In a recent paper, Tanaka, Suzuki and Himeno[21] calculated the boundary layers on a tanker model and on a container ship model, using two different methods on each hull. The first method was Himeno and Tanaka's[22] improved method, and the second was one proposed by Okuno[23]. Both computational techniques are of the integral type and differ primarily in that the Okuno method employs a "small crossflow" assumption while the Himeno and Tanaka improved method allows for large crossflow. With both computational methods, Tanaka et al. employ a curious technique in an attempt to account for the thick stern boundary layer. They set the velocity

$$v = v_1 + V_d - V_o,$$

where v_1 is computed from boundary layer theory and V_d is computed from potential theory (V_o is the value of V_d at the body surface). Of course such a solution will satisfy the body boundary condition and will be continuous at the edge of the boundary layer, but the mathematical justification for such a solution seems somewhat tenuous.

Figure 4 is a reproduction of their results for the container ship model. Although there is an encouraging qualitative agreement, the quantitative agreement is not acceptable. Their results for the tanker model showed even less agreement with the measured values and less agreement between the two numerical techniques. Furthermore, these results

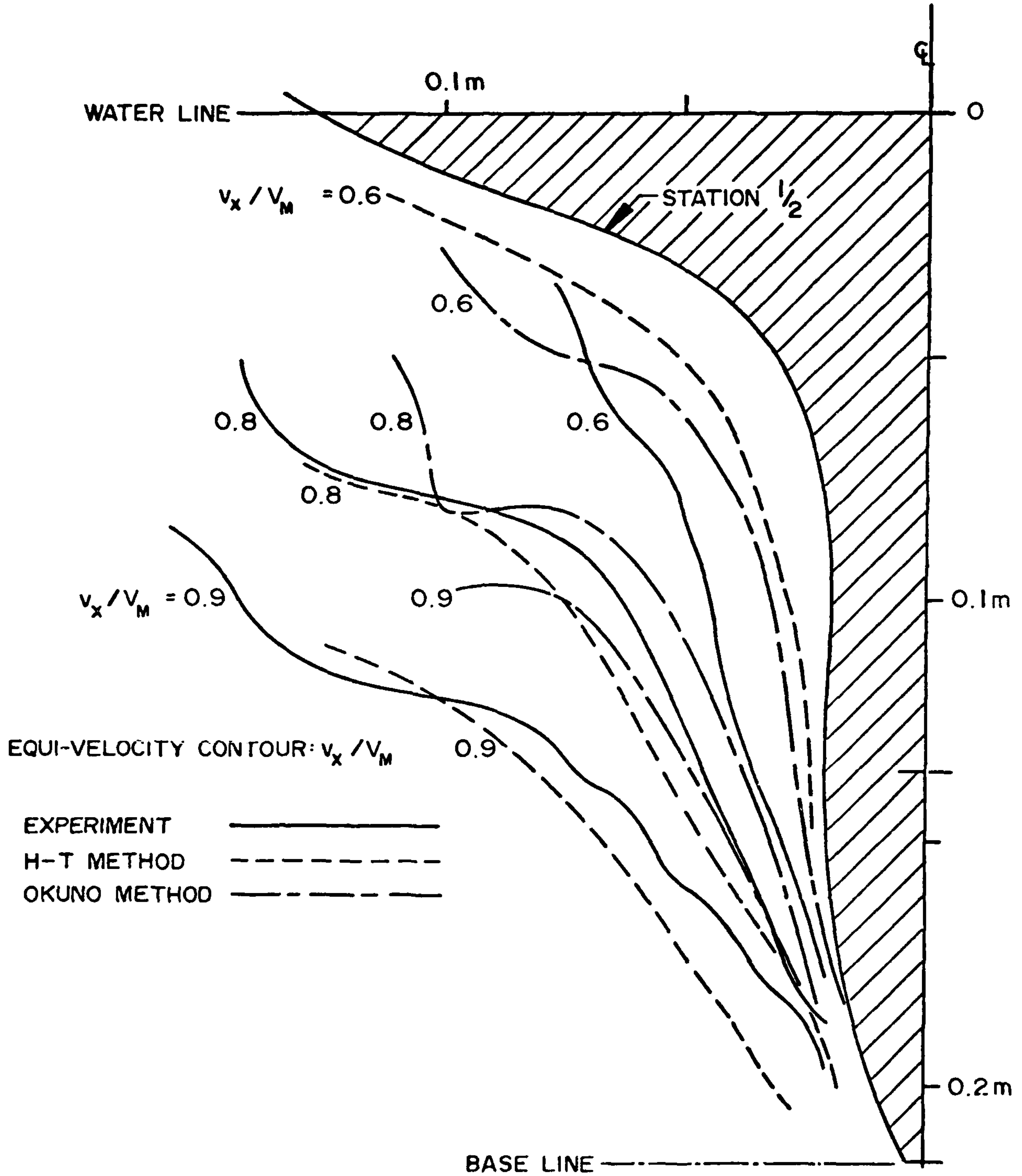

Figure 4: Boundary layer calculations for a model of a containership (ref. 21)

were obtained at station 0.5 (5% of the length forward of the A.P.), and one must expect that the agreement between calculated and measured values would worsen as one moved aft to the propeller position. The extent of the problem of a thick boundary layer on three-dimensional surface ships is indicated by the fact that Huang was able to use the thin boundary layer theory up to this same position.

Larsson[24] also used an integral method to calculate the three-dimensional turbulent boundary layer on a simple ship form. Since Larsson[25] had previously obtained boundary layer measurements on that hull form, Cebeci, Kaups, and Moser[26] also performed calculations on the hull. Cebeci's technique, however, is a finite difference method which employs an eddy viscosity model developed by Cebeci[27]. Although the two methods of calculating the boundary layer (Larsson's and Cebeci's) are of very different types, they produced remarkably similar results. Again we find that the numerical methods yield very good results forward of the stern only and will require some significant improvements before they are directly applicable to the determination of wake distribution, even on relatively fine hull forms.

As a final example of three-dimensional boundary layer calculations, Tanaka, Himeno, and Matsumoto[28] presented to the 14th ITTC results of their calculations on a Series 60, block 0.60, hull. A comparison of their results with measurements obtained by Stuntz, Pien, Hinterthan, and Ficken[29] at the propeller disk, although encouraging, showed substantial disagreement especially near the propeller hub.

Even though these results may seem to be disappointing, we should take heart in the fact that all of these methods for the calculation of three-dimensional turbulent boundary layers represent very significant advances over the techniques which were available to us just a few years ago. And even though the quantitative agreement with measured values is poor at the stern, the tendency towards good qualitative agreement may teach us a great deal about the proper manner in which to scale empirically model measurements up to ship scale.

Although significant advances have been made since 1935, we find that we must again repeat the words of Troost and admit that "For the present one shall have to make use of empirical coefficients to pass from model to ship."

MEAN WAKE - EMPIRICAL TECHNIQUES

A useful concept in the study of wake scale effects is the "mean wake". The mean wake is not an average of the effective wake distribution (although it is often compared to the mean nominal wake $\bar{w}_N$, which is an average value of the nominal wake distribution over the propeller disk), but is rather the effective wake, w_T or w_Q, found by the use of the thrust or torque identity. For simplicity, the subscripts T and Q will be dropped in this section and we will refer to the mean wake of the model w_m or the ship w_S.

Probably the simplest method for the estimation of the full scale mean wake, is one used by van Manen and Lap[30]. It was assumed that the change in the wake, Δw, could be estimated from the two-dimensional turbulent boundary layers on equivalent flat plates, and the mean wake of the ship was taken to be equal to the mean wake of the model minus Δw. The authors then incorporated form factors as a correction to the flat plate approximation. This method seems to yield reasonable results only if the ship is relatively fine.

There have been a number of methods which attempt to separate the mean wake into frictional and potential (or displacement) parts, $w = w_f + w_d$. These methods differ primarily in their approach to estimating w_d. The frictional wake is generally scaled in proportion to the frictional coefficient and the displacement wake is either held constant or almost constant. There are several good reviews of these techniques and the interested reader should consult Dyne[31], Yokoo[32], and Minsaas, Wermter, and Hansen[33].

Bowden and Davison[34] recently compared several of these methods, using a series of 38 sets of trials for single-screw ships as their data base. The methods which they compared were:

(1) Brard and Aucher[35,36]

$w_d = t_m \; [(1-w_m) + V_A/V]$ where t_m is the thrust deduction fraction of the model and V_A/V is to be determined as a function of the thrust loading coefficient.

(2) Dyne[31]

$w_d = \frac{t}{2} \; [(1-w_m) + \sqrt{(1-w_m)^2 + C_{Th}}]$ where C_{Th} is the thrust loading coefficient.

(3) Sasajima, et al.[37]

$w_d = t$ where it is assumed that the thrust deduction fraction is independent of scale.

(4) Modified Sasajima

$$w_d = t_m \; \left(\frac{1-w_{fs}}{1-w_{fm}} \right)$$

This method was introduced by Dickmann[38]

Of the four methods, the Sasajima method produced the best results for both the effective wake-thrust identity and effective wake-torque identity. Except for the modified Sasajima method which gave poorer results, all of the four methods produced similar results. The use of form factors and frictional correlation allowances were not found to improve the methods. Although there was considerable scatter in the results, the predicted effective wake-torque identity seemed quite good, while the effective wake-thrust identity was in error by about 0.05.

As useful as these methods might be for the prediction of full scale performance, even if perfected they will tell us little about the effect of scale upon the wake distribution; modern propeller design techniques require more than mean wake. Before we examine the existing techniques for the determination of full scale wake distributions, we will review the existing experimental data which will be useful in the testing of both empirical and analytical techniques.

EXPERIMENTAL DATA

There is, of course, a tremendous amount of data available on model scale nominal wake. Although such data are useful in the examination of the physics of the flow and in the evaluation of analytical boundary layer techniques, they are of little use in the examination of scale effects unless data are available at more than one Reynolds number. For this reason, we shall concentrate on those experimental investigations which present results at more than one scale, i.e., full scale investigations and geosim studies; or more than one Reynolds number, i.e., double model investigations.

FULL SCALE WAKE MEASUREMENTS

Yokoo[32] presents an excellent review of full scale measurements which were made prior to 1974. The interested reader should refer to the survey by Yokoo, as he gives a more complete review of many of the measurements which will be cited here.

Results of measured nominal wake for the 18 m training boat Yayoi-maru are presented in reference 39. Wake distributions were obtained at several hull surface roughnesses and it was found that the wake increases with increasing frictional coefficient. Since the wake normally decreases with increasing scale, it was shown that the effect of hull roughness could mask the effect of scale.

Measurements of full scale nominal and propelled wake distribution for the 73 m ($C_B = 0.56$) single screw ship Meteor were presented by Schuster, Grothues-Spork, Thieme, Schwanecke, and Wieghardt[40]. It was found that the difference between nominal and propelled wakes was quite large for this ship and, in fact, exceeded the change in the wake distribution due to scale.

Taniguchi and Fujita[41] measured the velocity in the boundary layer of a full form 160,000 DWT tanker. Although their measurements were taken at only one location on the hull which was too far forward to be properly referred to as the wake region, their measurements are most interesting in that they demonstrate the high degree of non-similarity of the boundary layer flow between ship and its geosim model.

Measurements of the boundary layers on three fishing boats (lengths of 12 m, 20 m, and 60 m) were presented at the 12th ITTC[42]. It was found that the velocity profiles on the parallel middle body were in good agreement with those predicted by the 1/7-th power law for flat plates. However, on the stern the boundary layer thickened rapidly and the measured profiles on two of the boats exhibited a "dent". This "dent" in the velocity profile appears to be associated with the formation of bilge vortices.

Yokoo et al.[43] presented measurements from two models and from the 167 m tanker ($C_B = .75$), Daishin-Maru. Their measurements included propelled wake distributions at various propeller loads. The variation with propeller load is quite visible even though their measuring station was 1.1 propeller diameters forward. The presence of bilge vortices was found at all scales and the change in the wake with scale was dramatic.

Measurements of the propelled wake of a high-block 160,000 DWT ore carrier and of its 12 m, 8 m, and 4m models were presented by the SR 107 Committee[44]. Bilge vortices were present at all scales with the vortices decreasing in size and increasing in intensity with increasing scale. The effect of propeller load seemed rather small, perhaps due to the location of the measuring station.

Canham[45] reported on a very extensive series of full scale tests on the Leander class frigate HMS Penelope, which was towed by a sister ship. There was very little difference between the nominal wake measured on the ship and on its model. Yokoo pointed out, in a written discussion, that this seemingly contradictory result was probably due to hull surface roughness, rather than a true lack of scale effects.

Measurements on a 250,000 DWT tanker with the propeller loaded and windmilling were presented by Restad and Kjellberg[46]. These results were quite different from those found by the SR 107 Committee on a similar hull form. Restad and Kjellberg saw little variation in the transverse velocities but substantial variation in the longitudinal component.

In another series of experiments on a high block ship, Namimatsu and Muraoka[47] measured the propelled wake of the 200,000 DWT tanker Ryuko-maru, as well as its 30 m model boat and its 7 m model. The measurements on the model were conducted at five separate longitudinal positions and show both the presence and the growth of the bilge vortices. Their results also indicate that there is very little change in the wake distribution due to propeller suction.

STUDIES WITH GEOSIMS AND DOUBLE MODELS

Since most of the full scale measurements which were just mentioned also included measurements at model scale, they may also be mentioned here (particularly references 43, 44, and 47). However, this section will include primarily studies for which there are no full scale data.

Of course, the most comprehensive investigation of geosims was the study of Victory ship models by van Manen and Lap[30]. They measured the nominal wake on seven models with scale ratios of 50, 40, 36, 30, 25, 23, and 18 and on one model boat with a scale ratio of 6. Another investigation of geosims, conducted by the SR 138 Committee[48], reported measurements on 2 m, 4 m, 7 m, and 10 m models of a high speed container ship. (Some of these results also appear in reference 21.)

Grothues-Spork[49] reported the results of two separate geosim studies. The first study included three models of the research vessel METEOR, for which there are full scale data (reference 40). The second study included four models of a tanker (scale 25, 35, 45, and 55) as well as a model boat (scale 7.5).

Since the range of Reynolds numbers, which are easily studied by means of towing tank tests with geosims, can be duplicated in the wind tunnel with a single double model, the number of recent reports on double model tests is considerable. The use of a double model requires a zero Froude number approximation and, therefore, this technique is especially suitable to the study of relatively low speed ships. (Also included in this section are studies which employ a single model with a flat plate at the waterline to simulate a zero Froude number condition.)

Matheson and Joubert[50], Hauke[51], Vollheim[52], Sachdeva and Preston[53], Hoffman[54], and Scragg[55], all present results on fairly full bodied tanker models, with velocity profiles obtained with either pitot tubes or hot-wires. Measurements on finer hull forms seem to be less prevalent, but we do have the study by Larsson[25], which has already been mentioned, as well as measurements on two models of the Lucy Ashton, plus an equivalent body of revolution obtained by Matheson and Joubert[56,57].

EFFECTS OF SCALE UPON THE WAKE DISTRIBUTION

If we go back and study the measured wake distributions at different scale ratios and for different ships (I recommend either of Yokoo's[2,32] survey papers for this purpose), we see that, not only do different hull shapes produce remarkably different wake patterns, but also seemingly similar hull shapes can produce very different wake distributions. Furthermore, both the effects of scale and the effects of propeller suction seem to be quite different for different hulls. Indeed, we even find disagreement between the various authors as to whether the effect of propeller suction is really significant (and if so, whether it is most significant in its impact upon the longitudinal or transverse velocities), and we even have one full scale study which reports finding negligible scale effects. Of course, part of the reason that we find such seemingly contradictory results can be attributed to the experimental difficulties inherent in any full scale investigation, but it would also appear that both scale effects and hull propeller interaction can be remarkably dependent upon both the basic hull shape and the local geometry.

An interesting example of the importance of local geometry was presented by Yokoo and Kawakami[58]. They measured model scale nominal wake distributions for a twin-screw container ship model with four different propeller bossing angles. Although the longitudinal velocity distribution remained virtually unchanged at different bossing angles, the tangential component changed radically. They suggested the possibility of obtaining rather large changes in the effective wake by determining the optimum bossing angle. In a companion paper by the same authors[59], the effects of length-to-beam ratio, block coefficient, and hull propeller clearance upon wake distributions were investigated. As expected, the block coefficient had the greatest effect.

Yokoo, Takahashi, and Kawakami[60] used two geosims each for four different tanker models to investigate the relationship between stern shape and scale effects. Using two U-shaped sterns and two V-shaped sterns, they noted greater hull propeller interactions on the fuller sterns and the lack of bilge vortices on the V-shaped sterns.

In a more comprehensive investigation, Dyne[61] also used models with both U-shaped and V-shaped sterns to study scale effects. To simulate different scales, he used both the towing tank and later the cavitation tunnel (to obtain a higher Reynolds number) and finally approximated a still higher Reynolds number by removing some of the parallel middle body of the model. Again it was found that propeller suction effects were greater on the U-shaped sterns and that the V-shaped sterns did not produce bilge vortices.

Dyne also attempted to predict the wake distribution at full scale by two different techniques. Both techniques rely upon the assumption[62] that the wake can be separated into three parts: displacement wake, wave wake, and frictional wake. Usually it is also assumed that the wave wake is either scale independent or negligible and that the effect of scale on the displacement wake is also small. The displacement wake has been assumed, by various researches, to be equal to the wake calculated from potential flow theory, or measured from astern towing tests, or as in the present case, determined from pressure measurements:

$$w_N = 1 - \sqrt{\frac{H - p}{\frac{1}{2} \rho V^2}} \qquad w_f = 1 - \sqrt{\{H - p_0\}/\{\tfrac{1}{2} \rho V^2\}}$$

$$w_d = w_N - w_f$$

where H is the total pressure, p is the local static pressure and p_o is the static pressure at infinite upstream.

In the Dyne extrapolation method, he measures the local wake at a given radius and angular position for several "effective" scales ("effective frictional coefficient"). He then plots a curve of local wake versus frictional coefficient using measured data points and a calculated "ideal wake" at zero frictional coefficient. Once this curve is constructed, he simply reads the full scale local wake from the curve at the ship's calculated frictional coefficient. Of course, he must construct many such curves to obtain the value of the local wake at a sufficient number of radii and angular positions to allow for the determination of the full scale wake over the entire propeller disk.

In the Sasajima method[63] (Dyne uses a measured displacement wake rather than the wake calculated from ideal flow theory), one simply sets the displacement wake as scale independent and contracts the frictional part toward the ship's centerplane by an amount equal to the ratio of the ship's frictional coefficient to the model's frictional coefficient.

Dyne found that the two methods produced comparable results for the model with the V-shaped stern, but there were significant differences between the predictions for the U-shaped stern. This is probably due to the fact that the Sasajima method is basically treating the problem as if it were two-dimensional, while the Dyne method is truly an extrapolation of three-dimensional values, and of course, three-dimensional effects are more important on the U-shaped stern. Since there were no full scale data available, we cannot be certain which method produced the better results. The Sasajima method has been used on two cases for which full scale data were available (see reference 44 and 47), on one case the agreement was fairly good while on the other ship the results were poor.

Hoekstra[64] presents a third method for the determination of the full scale wake distribution from model scale data. Hoekstra argues that Sasajima's contraction toward the centerplane requires a two-dimensional assumption which can be avoided. By Fourier analysis, Hoekstra separates the wake into basic components, even harmonics and odd harmonics. He then argues that the basic components should be contracted radially inward toward the propeller hub, that the even harmonics should be contracted toward the centerplane, and that odd harmonics should be contracted upwards toward the hull above the propeller. Although this method is more complex, it is readily adaptable to modern computer techniques.

Hoekstra also breaks with the traditional assumption of independent frictional, wave, and displacement wakes. He points out that this is not a very realistic assumption and that it is probably better to contract the entire wake rather than just the frictional part. Hoekstra's technique is also the only one which specifically addresses the problems of bilge vortices. To handle the presence of bilge vortices, he applies a correction to the contraction factors which is based upon the Strouhal number. As in the other methods, Hoekstra's contraction factors are based upon the ratio between the frictional coefficients of the ship and its model.

Results are presented for both the Victory ship series[30] and the Meteor[49], as well as a tanker model for which no full scale data were available. The agreement was relatively good for the Victory series, and fair for the Meteor. Based upon a recent study of the bilge vortex scale effect by Huse[65], the methods of Hoekstra and Dyne appear to yield results which are qualitatively correct, with respect to the displacement of the wake peak caused by a change of scale, while Sasajima's method will not allow for the downward displacement of the vortex.

All of these methods employ a scale factor which is based upon the so-called "equivalent flat plate". Huang[66] pointed out that this was really an incorrect approach, since the thick boundary layer in the stern region does not follow the well known formulas for turbulent boundary layers on flat plates. He points out that empirical methods for axisymmetric boundary layers are somewhat more accurate. Since considerable effort has already been directed toward the determination of a frictional coefficient based upon equivalent bodies of revolution (see Nakayama, Patel, and Landweber[67], and Granville[68,69]), this seems like a technique which might yield some immediate improvement.

All of the empirical techniques which have been presented here are capable of yielding full scale values of the nominal wake distribution based upon model scale measurements. It is difficult to assess the accuracy of any of these methods due to the extremely limited amount of full scale nominal wake data which are available. However, the use of any of these methods is preferable to neglecting scale effects.

THE INTERACTION BETWEEN THE HULL AND PROPELLER

Thus far, very little has been said about the determination of effective wake. All of the experimental data which have been mentioned (with the exception of the work by Huang[4-7]) were presented either in terms of nominal or propelled wake. The theoretical boundary layer calculations are still not perfected for the bare hull and have yet to address propeller suction effects, and the empirical techniques have been aimed at either mean wake calculations or scale effects only (with the exception of Hoekstra's work which will be mentioned shortly). Furthermore, we have even seen experimental measurements which seem to indicate that propeller suction effects might be negligible in certain instances.

There would appear to be something less than a general agreement among the various authors as to the importance of propeller suction. Perhaps an explanation can be found in a recent paper by Sasajima and Nagamatsu[70]. They traced streamlines in open water with a propeller operating at various loads. They observed a significant contraction of the streamlines upstream of the propeller, but this contraction took place in a very short distance immediately in front of the propeller. Their results indicate that, if one's measuring station were as much as one propeller diameter upstream of the propeller station (a typical distance in full scale measurements), it might be very difficult to measure the difference between nominal and propelled wake. It is not surprising, then, that some studies have seen little effect of propeller suction , while those studies which employed a measuring station nearer the propeller saw dramatic effects.

Probably the most dramatic change in flow pattern will occur when the change in pressure distributions due to the propeller is just great enough to prevent the onset of boundary layer separation. Grothues-Spork[71] observed just such a situation in a study which used three geosims of a very full stern tanker. At all three scale ratios, there was observed an area of separated flow forward of the propeller station which disappeared when the propeller was fully loaded.

Actual attempts at the determination of the effective wake distribution are rather rare. Hucho[72] measured the wake behind bodies of revolution and a flat plate with and without a propeller in operation. His results show a substantial reduction in the boundary layer thickness due to the propeller, but further analysis is necessary as he made no attempt to subtract out the propeller induced velocity from the measured profiles.

In the previous section, three methods of approximating the full scale nominal wake were outlined. Of these three, only Hoeksta[64] addresses the need to determine the effective wake. He recommends the use of a concentric contraction of the full scale wake field by a factor h where

$$\tfrac{1}{2} h^2 = \left(1 + \sqrt{1 + C_{TN}} \right)^{-1}$$

This factor is obtained from momentum theory and the resulting wake field is intended to approximate the full scale propelled wake. Although he recommended a method of determining the induced velocity by approximating the propeller and hull by an actuator disk near a flat plate, he does not attempt to go through the calculations.

More recently, Hoekstra[73] took a different approach. He replaced the propeller with a diffuser, in which he placed a five-hole pitot tube. He then measured the (simulated) propelled wake at model scale. The induced velocity is calculated from potential flow theory. His calculated induced velocity approximates the propeller induction in open water averaged over the propeller disk and although this is not likely to be a very accurate representation of the real propeller induced velocity behind the model, the author showed a clear understanding of the need to determine the effective wake distribution.

Another method of calculating the effective wake distribution has been suggested by Raestad[74]. The method is based upon a streamline contraction technique, but the author fails to make any distinction between effective wake and propelled wake. Since he fails to subtract out the induced velocity, it is not surprising that the technique yields calculated values of "effective wake" which are too low (he is actually calculating propelled wake). He finally introduces a correction factor to improve the situation, but this is simply an improper specification of the problem.

Titoff and Otlesnov[75] proposed a method of estimating the effective wake and the measured induced velocities in open water. Although they presented a proper specification of the problem, it would appear that the use of the open water induced velocity, as an approximation to the true induced velocity, can lead to some rather poor results at some locations on the propeller disk. This is due to the fact that near the hull the propelled velocity might be less than the propeller induced velocity in open water. This problem might be corrected by measuring the induced velocity behind a wake screen, rather than in open water as suggested by Morgan[76].

The interested reader should consult the reviews by Huang[66] and Morgan[76]. In conclusion, it would appear that the work of Huang[4-7] is the only truly successful attempt at the calculation of the effective wake distribution.

CONCLUSIONS

Clearly, we are still a good distance away from being able to predict the effective wake of an arbitrary hull form at an arbitrary Reynolds number. As of this writing, the state of the art is limited to the prediction of effective wake (given the nominal wake at the appropriate scale ratio) for deeply submerged bodies of revolution. To a lesser extent, the prediction of the nominal wake of deeply submerged bodies of revolution (at an arbitrary Reynolds number) is also possible, provided only that the body is not excessively full.

It would seem that the next logical extension of the methods which have been applied successfully to bodies of revolution would include the effects of the stern appendages. It might be possible to include these effects as a perturbation about the bare hull results, but such an approach is far from trivial since the flow is dominated by different physical phenomena at inner and outer propeller radii. At the propeller tip, the perturbation would be dependent upon the velocity defect created by the appendage, but near the propeller hub, the flow is dominated by the root vortices of the appendages.

It is possible that many transom stern surface ships are more amenable to theoretical predictions of nominal wake (especially for the bare hull situation) than the bodies of revolution which have been given so much attention. This is due to the fact that such hull forms often have the propellers located at a station where the rapid thickening of the stern boundary layer is not a severe problem. On such a hull form, the prediction of nominal wake may very well become a problem of predicting the interaction of the hull boundary layer with the appendages.

For relatively fine surface ships (without strong bilge vortices) there may be some improvement in current prediction schemes offered by an equivalent body of revolution approach. For the full stern ships, the presence of bilge vortices produces a further complication since it would appear that the displacement of the vortices with increasing Reynolds number (or with increasing propeller loading) is quite different from the displacement of stream surfaces in the absence of bilge vortices.

For the present, it would appear that the general approach which offers the greatest chance of success is a three-step, empirical/analytical approach which may be outlined as follows:

(1) Measurement of model scale nominal wake,

(2) Estimation of full scale nominal wake from model scale measurements,

(3) Analytical determination of full scale effective wake.

There is, of course, a great appeal to the use of purely theoretical methods, but these methods appear to be of rather limited use in the near future. However, in the long run, it is believed that theoretical techniques will enable us to achieve finally our goal of prediction of the effective wake of an arbitrary hull form.

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